Estimation of daytime surface fluxes of radiation and heat at Anand during 13–17 May 1997

S. G. Nagar[†,#], P. Seetaramayya[†], A. Tyagi* and S. S. Singh[†]

[†]Indian Institute of Tropical Meteorology, Dr Homi Bhabha Road, Pashan, Pune 411 008, India
*Indian Air Force, Pune 411 032, India

In this paper an attempt has been made to estimate radiative fluxes of short wave, long wave as well as non-radiative fluxes such as sensible heat flux and the surface soil heat flux during daytime over a bare soil at a tropical station Anand (22°35′N, 72°55′E, 45.1 m asl), for the dry convective period 13–17 May 1997. The site-specific parameters such as attenuation coefficients, albedo, transmissivity, etc. are obtained with the help of observations during 2–11 May 1997. The results are compared with real time data. Comparison of estimated and observed radiative fluxes showed a good agreement. The root mean square error (rmse) is 3% for incoming solar radiation and 8% for net radiation. The sensible heat flux is in general underestimated. The surface soil heat flux values estimated by two different methods are fairly close to each other. The surface temperature estimated by Fourier's law for heat conduction shows good agreement with the observed values with rmse 5%.

THE interaction between the earth's surface and overlying atmosphere takes place through the exchange of surface fluxes of momentum, moisture and heat into the atmosphere and vice versa. The surface fluxes generally determine to a great extent the state of the planetary boundary layer (PBL) and are treated as primary surface boundary conditions for weather prediction and climate studies. These fluxes can be measured. However, such measurements are not usually available. Therefore, they are computed by available routine surface weather data. In a weather forecast model the fluxes are generally parameterized in terms of variables predicted by the model.

A variety of models and techniques have been developed for computing the surface fluxes[1–4]. The majority of these models are one-dimensional descriptions of time evolution. The measurement campaigns (e.g. Wangara 1967, Kansas, 1968, Minnesota 1973, Koorin 1974, Cabauw and De Bilt 1975–1979, Valladolid 1982, Bao 1983, Osu 1995, etc.) helped the validation of these models. In India, field experiments such as MONTBLEX-90 (Monsoon Trough Boundary Layer Experiment), VEBEX: 95–96 (Vegetation and surface Energy Balance Experiment) and LASPEX-97 (Land Surface Processes Experiment) are conducted over land surfaces. Using these data sets several research studies are documented[5–7]. Padmanabhamurty *et al.*[8] have estimated surface temperatures at five grid stations using LASPEX-97 data for the winter period 13–17 February 1997, whereas Satyanarayana *et al.*[9] made an attempt to simulate the characteristics of the PBL at Anand during this winter period. Nagar *et al.*[10] have studied the evolution of atmospheric boundary layer at Anand for the summer period 13–17 May 1997. Further, Nagar *et al.*[11] have computed the height of the daytime convective boundary layer by a one-dimensional model for the bare soil surface for the same summer period.

In the present study, an attempt is made to compute various fluxes such as incoming short wave radiation, net radiation, sensible heat flux, surface soil heat flux and surface temperature at Anand during 13–17 May 1997 at a bare soil site under dry convective condition. The results are then compared with the observed data collected during LASPEX-97 at the same site.

Experimental site and description of data

LASPEX-97 was conducted during the period January 1997 to March 1999 at Anand (22°35′N, 72°55′E, 45.1 m asl), Gujarat, in the western part of India. The experiment aims to collect surface and subsurface atmospheric–hydrological data and to test parameterization schemes for land surface processes such as energy exchange, radiative and non-radiative heat fluxes for their improvement and further development. The site is an agricultural land located in the Gujarat Agricultural University campus, Anand, which has loamy sand soil. The soil contains 80.67% sand, 8.73% clay and 6.93% silt with a bulk density of 1.55 Mgm^{-3}, thermal conductivity 0.944 $Wm^{-1} K^{-1}$, thermal diffusivity $0.508 \times 10^{-6} m^2 s^{-1}$, volumetric heat capacity $1.859 \times 10^6 Jm^{-2} K^{-1}$, field capacity 17% and wilting point 5%. At this site, a 10 m tower was installed. Different sensors to measure air temperature, humidity, wind speed and direction have been installed at 1, 2, 4 and 8 m height. A Metek (Germany) sonic anemometer was mounted on the same tower at 9.5 m level. The sonic anemometer is a sophisticated, fast-response turbulence instrumentation which measures the fluctuations in the temperature and in all the three

[#]For correspondence. (e-mail: nagar@tropmet.res.in)

components of wind. Radiation instruments were fitted at 2 m height on a separate stand. Soil temperatures were measured at the surface and at the depths 5, 10, 20, 40 and 100 cm. The soil heat flux at 5 cm depth was measured by Thornthwaite heat-flux plates. More details of the experiment are available in Shekh *et al.*[12].

The data were recorded automatically using a data-logger that had 32 analogue channels and 5 digital channels powered by a battery and a solar panel. The data-logging was done every second for all channels and averaged for one-minute and stored in a 2 MB memory module which was later downloaded on to a personal computer and stored permanently. In one-minute averaging mode, the memory module could store five days' continuous data. Continuous tower data at one-minute interval during intensive observational periods (IOPs) for five days from 13 to 17 of each month were collected at Anand. In all, 12 IOPs were conducted from January 1997 to October 1997, December 1997 and February 1998. Other than the tower data, radiation data such as short wave radiation, long wave radiation and net radiation, soil heat flux at 5 cm depth and sonic anemometer data at 9.5 m have been collected at Anand. The sonic anemometer data are collected only during IOPs. The tower data of February, May, July, September and December 1997 were processed and made available to the users.

We have selected the month of May for the present study, as it is the hottest month of summer and clear sky conditions prevailed over Gujarat during this time. During the period 13–17 May 1997 the air temperature varied from 22.5 to 40.2°C, while the surface temperature varied from 18.9 to 58.9°C, giving a diurnal range of 40°C. The surface temperature exceeded 58°C in the afternoon. The incoming short wave radiation exceeded 900 Wm^{-2} at noon and wind speeds were less than 4 ms^{-1}. Consequently, the surface was highly unstable during the daytime. But no significant weather activity was noticed and no precipitation occurred during the entire study period[11].

For the present study, the one-minute averaged data are further averaged for 30 min intervals at 0730, 0800, 0830, . . . 1730, 1800, 1830 IST. Similarly, the temperature and wind data from sonic anemometer (averaged for 10 min) are further averaged for 30 min intervals. Daytime is defined when the sensible heat flux changes from negative to positive values. It is observed that during the study period the heat flux becomes positive around 0800 IST and it again changes sign and becomes negative at around 1730 to 1800 IST. Hence, in the present study we will present the results for daytime hours between 0830 and 1730 IST (without considering sunrise and sunset).

Computational method

We have used the standard formulae for computation of incoming short wave radiation, net radiation, surface soil heat flux, sensible heat flux and surface temperature. The accuracy of the estimated values is assessed by root mean square error (rmse) and correlation coefficient.

Incoming short wave radiation

Incoming short wave radiation (K^{+}) reaching at the surface of the earth is a function of solar zenith angle, surface turbidity, etc. and is given by[2]

$$K^{+} = ST_k \sin \Phi, \tag{1}$$

where S is the solar constant which ranges from 1360 to 1380 Wm^{-2}, T_k is the net sky transmissivity and Φ is the solar elevation.

In the present study we have used $S = 1373$ Wm^{-2}.

For clear sky, T_k is defined as

$$T_k = K^{+}/S \cdot \cos Z, \tag{2}$$

where Z is the solar zenith angle.

At many meteorological stations, (K^{+}) is measured. But when such measurements are not available, it can be estimated as a linear function of sine of the solar elevation for clear skies, with its empirical coefficients relating to turbidity. It is estimated as[1,13]

$$K^{+} = a_1 \sin \Phi - a_2, \tag{3}$$

where a_1 and a_2 are the empirical coefficients known as attenuation or turbidity coefficients.

Net radiation

The net radiation (Q^*) at the earth's surface is denoted by an algebraic sum of both downward and upward components of the short wave and the long wave radiation flux densities. Upward and downward radiations are functions of soil emissivity, ground temperature, atmospheric vapour pressure and temperature. Thus,

$$Q^* = (1 - r)\, K^{+} + L\downarrow - L\uparrow, \tag{4}$$

where r is the surface albedo, $L\downarrow$ is the downward long wave radiation and $L\uparrow$ is the upward long wave radiation. The quantity $L\downarrow$ is given as[14],

$$L\downarrow = \sigma T_a^4 \left[0.684 \frac{e_a^{1/9}}{\left(1+\dfrac{H}{H_w}\right)^{1/9}} \left\{ 1+\frac{0.20(1-0.117\gamma)}{\left(1+\dfrac{H}{H_w}\right)} \right\} + 0.0656 - 0.0003(T_a - 288) \right], \tag{5}$$

where $\sigma = 5.67 \times 10^{-8}$ Wm^{-2} K^{-4} is the Stefan–Boltzmann constant, T_a is the air temperature in Kelvin at the measurement level at screen height 1.2 m, e_a is the atmospheric vapour pressure, H is the atmospheric scale height, H_w is the water vapour scale height and γ is the temperature lapse rate. Observations by Smith[15] indicate that the seasonally averaged value of H/H_w is close to 4.0 in the latitude range 10 to 40°.

The upward long wave radiation $L\uparrow$ follows from Stefan–Boltzmann's law as

$$L\uparrow = \varepsilon_s \sigma T_s^4, \tag{6}$$

where ε_s is the emissivity of the surface and T_s is the surface temperature. The value of ε_s is taken as 0.96 following Brutsaert[16].

Sensible heat flux

The sensible heat flux (Q_H) was measured directly by the sonic anemometer at 9.5 m using eddy correlation technique. It can also be described by standard bulk aerodynamic transfer equation. Thus it is expressed as a function of the temperature gradient between the surface and the reference level (9.5 m) given by

$$Q_H = (\rho c_p/r_{aH})\,(T_s - T_{9.5}), \tag{7}$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, r_{aH} is the aerodynamic resistance to heat transfer between the surface and the reference height and $T_{9.5}$ is the temperature at 9.5 m. The aerodynamic resistance (r_{aH}) to heat transfer is expressed as[17],

$$r_{aH} = [\ln(z/z_T) - \Psi_H][\ln(z/z_o) - \Psi_M]/(k^2 u_{9.5}), \tag{8}$$

where z_T and z_o are the surface roughness lengths for transfer of sensible heat and momentum respectively. Ψ_H and Ψ_M are the diabatic profile correction factors for heat and momentum respectively, k is the von Karman constant (= 0.4) and $u_{9.5}$ is the wind speed at 9.5 m level. The diabatic profile correction factors for heat and momentum were calculated following Paulson[18] for unstable conditions as,

$$\Psi_H = 2\ln[(1 + y)/2], \tag{9}$$

$$Y_M = 2\ln[(1 + x)/2] + \ln[(1 + x^2)/2] - \arctan x + \pi/2, \tag{10}$$

where

$$x = (1 - 16\zeta)^{1/4} \text{ and } y = (1 - 9\zeta)^{1/2}. \tag{11}$$

ζ is an index of atmospheric stability ($\zeta < 0$ for unstable conditions and $\zeta > 0$ for stable conditions) given by

$$\zeta = z/L = kzg\theta^*/(Tu^{*2}), \tag{12}$$

where L is the Monin–Obukhov length and θ^* and u^* are temperature and velocity scales respectively.

Surface soil heat flux

The surface soil heat flux (Q_G) cannot be measured easily and is usually obtained from the heat flux $Q_{Gz'}$ at a small depth z'. The sub-surface heat flux $Q_{Gz'}$ at any depth z' can be described by Fourier's law for heat conduction in a homogeneous body as,

$$Q_{Gz'} = -k_s \partial T_s/\partial z' \tag{13}$$

where k_s is the thermal conductivity of the soil. Then the surface soil heat flux (Q_G) is calculated after solving the differential equation describing one-dimensional heat conduction in the homogeneous soil[19],

$$C_s\,\partial T_s/\partial t = -\partial Q_{Gz'}/\partial z' = \partial(k_s \partial T_s/\partial z')/\partial z', \tag{14}$$

where C_s is the volumetric heat capacity of the soil and t is the time. C_s is computed following Garratt[20] as

$$C_s = C_{sdry}(1 - w_s) + w\,C_w, \tag{15}$$

where C_{sdry} is the volumetric heat capacity of dry soil, w is the volumetric moisture content, w_s is the saturated value of w and C_w is the volumetric heat capacity for water. The value of w is 0.10 $m^3\,m^{-3}$ which is the mean value of the observed mean surface water content at Anand during 13–17 May 1997.

Combining eqs (14) and (15) and considering

$$T_s = T_{sm} + A_o \cos((t_{local} - t_{max})\pi/24), \tag{16}$$

the surface soil heat flux at $z = 0$ can be obtained from eq. (13) as

$$Q_G(\text{Fourier}) = A_o(k_s C_s \omega)^{1/2} \sin(\omega t + \pi/4), \tag{17}$$

where ω is the angular velocity of the earth's rotation (7.292×10^{-5} rad s^{-1}), $T_{sm} = (T_{smax} + T_{smin})/2$ is the daily mean surface temperature, $A_o = (T_{smax} - T_{smin})/2$ is half of the surface temperature amplitude, t_{local} is the local time in hours, and t_{max} is the local time at which the maximum surface temperature is observed. T_{smax} and T_{smin} are maximum and minimum surface temperatures respectively.

The maximum Q_G occurs three hours before the maximum surface temperature for diurnal wave and the maximum surface temperature is generally observed at 1400 h to 1500 h local time. This corresponds to the lag of $\pi/4$ that is found between the solutions of temperature and ground flux for sinusoidal forcing, assuming that the maximum ground heat flux occurs around midday[3].

The surface soil heat flux can also be calculated using the measured soil heat flux at 0.05 m depth ($Q_{G0.05}$) and a correction term for heat divergence between the surface and 0.05 m layer following Stathers *et al.*[19] and Braud *et al.*[21] as,

$$Q_G(\text{Divergence}) = Q_{G0.05} + (C_s \Delta T_{save}/\Delta t)\Delta z, \tag{18}$$

where T_{save} is the average temperature of the 0.05 m layer, $\Delta t = 0.5$ h and $\Delta z = 0.05$ m.

Soil temperatures measured at the surface and at 0.05 m depth are used for the computation of Q_G.

Surface temperature

The surface temperature (T_s) is calculated using eq. (16).

Results

Incoming shortwave radiation

Transmissivity (T_k): The mean T_k value at the true solar noon ($Z = 0$) computed from the observed values of the incoming short wave radiation during 2–11 May 1997 at Anand is 0.659. This value is close to that estimated by Mani and Rangarajan[22] for a nearby station at Ahmedabad. They have obtained the mean value of T_k as 0.681 for Ahmedabad during May.

Attenuation coefficients: The attenuation coefficients (a_1 and a_2) describe the attenuation of solar radiation in the atmosphere by water vapour, trace gases and dust particles. As such they show geographical variations. Table 1 shows the values of a_1 and a_2 observed over different regions in the world and also at Anand. The half-hourly average values of incoming short wave radiation at Anand during 2–11 May 1997 for the solar elevation angle $\phi > 10°$ are used to compute the coefficients a_1 and a_2 by means of a least square regression technique. The least square estimates of a_1 and a_2 are 1034 Wm^{-2} and 111 Wm^{-2} respectively, and the rmse of estimates of incoming short wave radiation with these coefficients is 43 Wm^{-2}. This rmse is 6% of the observed mean value of incoming short wave radiation with the correlation coefficient 0.98. These values of a_1 and a_2 are close to those obtained by Nagar *et al.*[13] over the monsoon trough region, where $a_1 = 1060$ Wm^{-2} and $a_2 = 106$ Wm^{-2} (Table 1).

Using the estimates of a_1 and a_2 determined for Anand, the half-hourly values of incoming short wave radiation are estimated and compared with the observed values for the period 13–17 May 1997. The rmse is 23 Wm^{-2}, which is 3.2% of the observed mean value of the incoming short wave radiation. Figure 1 *a*, *b* shows the scatter plots of observed against estimated values of incoming solar radiation for observations averaged over 30 min estimated with eqs (1) and (3) respectively. It is seen that Figure 1 *a* shows slightly large scatter compared to Figure 1 *b*. The rmse is 3.9% when eq. (1) is used, whereas it is only 3% when eq. (3) is used. This shows that the empirical formula (eq. (3)) can be used with confidence when the measurements are not available. Figure 2 shows the daytime course of K^+ for 15 May 1997 (representative of 13–17 May 1997). It is seen that the estimated values of K^+ by eqs (1) and (3) are in general more or less close to the observed values throughout the day. The difference between estimated and observed values increases after noon. The observed maxima around 1230 to 1330 IST is 907 Wm^{-2}, whereas estimated values by eqs (1) and (3) are 903 Wm^{-2} and 920 Wm^{-2} respectively.

Table 1. Attenuation coefficients a_1 and a_2 for different regions during dry period

Location	a_1 (Wm^{-2})	a_2 (Wm^{-2})	Reference
Boston (42°13′N, 71°07′W)	1098	65	30
North Atlantic (52°30′N, 20°W)	1100	50	31
Harrogate (54°N, 1°30′W)	990	30	32
Hamburg (53°38′N, 9°50′E)	910	30	33
De-Bilt (52°06′N, 5°11′E)	1041	69	1
Aberporth (52°06′N, 4°30′W)	1024	54	34
Finnigley (53°N, 1°W)	902	36	34
Stornoway (58°12′N, 6°24′W)	979	45	34
Monsoon trough region (15–30°N, 70–90°E)	1060	106	13
Anand (22°35′N, 72°55′E)	1034	111	Present study

Surface albedo: The albedo (r) is regarded as a surface property. It plays a key role in the surface-energy budget. In general it depends upon solar zenith angle and other surface characteristics. Short vegetation shows variation in albedo with solar altitude, whereas bare soil has a nearly constant value of albedo. The surface albedo

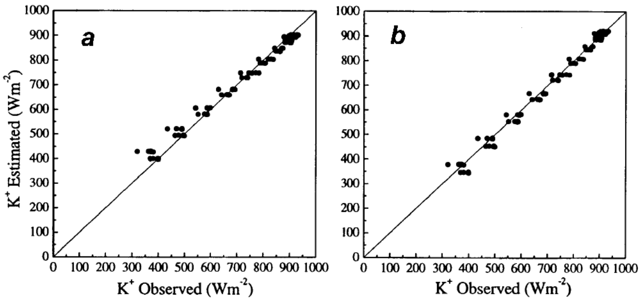

Figure 1. Comparison of observed incoming short wave radiation (K^+) with its estimated values from (***a***) eq. (1) and (***b***) eq. (3) during 13–17 May 1997 at Anand.

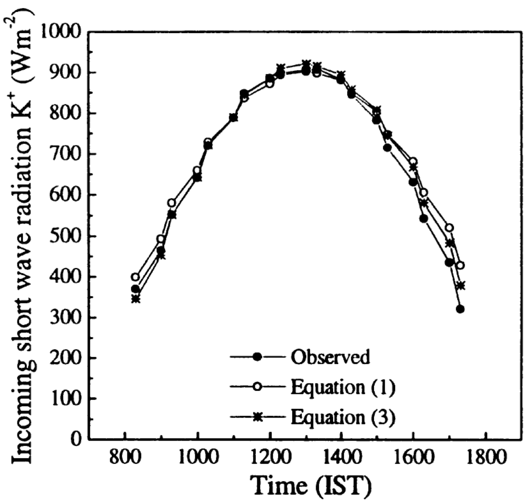

Figure 2. Daytime course of incoming short wave radiation (K^+) on 15 May 1997 at Anand (observed and estimated).

calculated as the ratio of daily totals of reflected (outgoing) to incident (incoming) short wave radiation for the period 2–11 May 1997 was 0.21 at Anand. The value of albedo can also be estimated as the slope of the linear regression equation relating the reflected short wave radiation (rK^{+}) to the incident short wave radiation (K^{+}). This method of calculation allows any diurnal variation of the albedo to be estimated from the curvature of the observed relationship and its distance from the origin. Figure 3 shows the scatter plot of outgoing short wave radiation versus incoming short wave radiation. It is seen from Figure 3 that the surface albedo is nearly constant without any diurnal variation over bare soil at Anand. The value of surface albedo as the slope of the straight line in Figure 3 is found to be 0.21. It is to be noted that Mani and Rangarajan[22] have assumed a mean value of 0.20 for the surface albedo for all Indian stations on the basis of measured values of albedo (ranging from 0.15 to 0.25) for several locations in India. Idso *et al.*[23] obtained the value of albedo as 0.28 for bare soil at Minnesota (44°59′N, 93°11′W) on clear days, whereas Polavarapu[24] obtained the mean albedo value of 0.211 for clear days at three stations in Southern Ontario. Holtslag and van Ulden[1] have used the value of $r = 0.23$ (which is a normal value for short grass) at Cabauw and De-Bilt.

Net radiation

Figure 4 *a* shows the scatter plot of observed against estimated values of Q^* with eq. (4), in which we have used eq. (1) to compute K^{+}. For the scatter plot in Figure 4 *b*, K^{+} is computed from eq. (3). It is seen that scatter in both the figures is more or less similar. This is due to the fact that rmse is only 3 to 4% in the estimation of K^{+}, as discussed earlier. The rmse between the estimated and observed values of Q^* is 11% and 8% in Figure 4 *a* and 4 *b* respectively. Figure 5 shows the daytime variation of Q^* for 15 May 1997. It is seen that estimated values of Q^* are slightly higher than the observed values during morning and evening hours, whereas they are lower during noon.

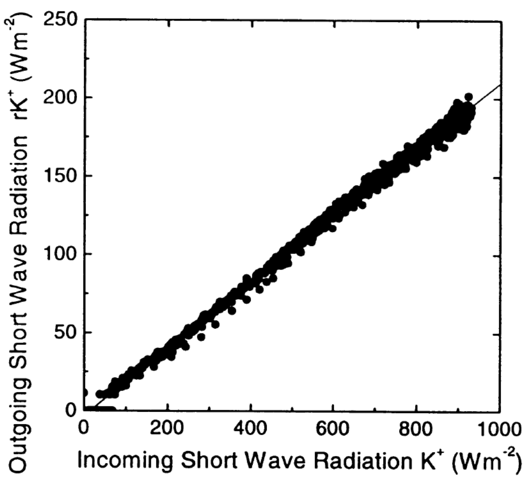

Figure 3. Scatter plot of outgoing short wave radiation (rK^{+}) versus incoming short wave radiation (K^{+}) during 2–11 May 1997 at Anand.

Sensible heat flux

Roughness length for momentum (z_o): Following Kusuma *et al.*[25], z_o is obtained from the relation

$$u/u^* = (1/k) \cdot [\ln(z/z_o) - \psi_M(z/L)]^{-1}, \quad (19)$$

in which the function ψ_M is computed from eq. (10). Using the observations of $u_{9.5}$, u^* and z/L from sonic anemometer during 13–17 May 1997, the average value of z_o at Anand is 0.2914 m, which is nearly same as that estimated by Gupta *et al.*[26]. They have obtained the value of z_o as 0.2893 for 25 February 1997 at Anand using remote sensing data.

Roughness length for heat (z_T): The distinction between z_o and z_T is due to different mechanisms between the transfer of momentum and heat. In general z_o is considerably

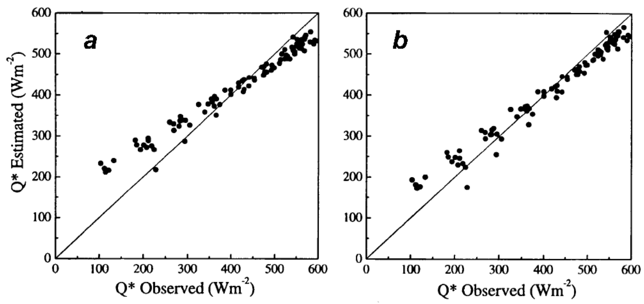

Figure 4. Comparison of observed net radiation (Q^*) with its estimated values from eq. (4) during 13–17 May 1997 at Anand. Values of K^{+} estimated from (*a*) eq. (1) and (*b*) eq. (3) are used in eq. (4).

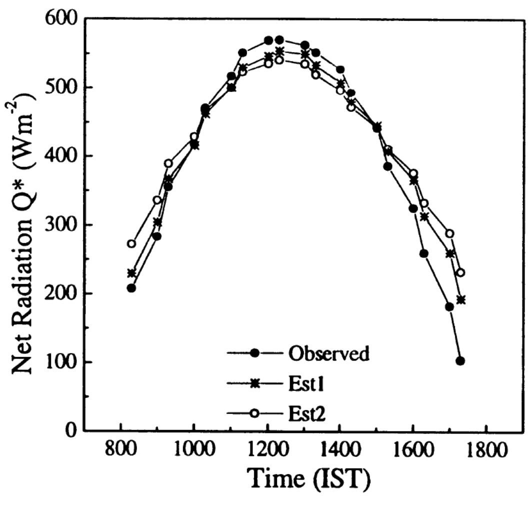

Figure 5. Daytime course of net radiation (Q^*) on 15 May 1997 at Anand (observed and estimated). Estl, Estimated values of K^{+} (from eq. (1)) are used in eq. (4).; Est2, Estimated values of K^{+} (from eq. (3)) are used in eq. (4).

different from z_T due to the fact that the transport of momentum is partly related to turbulent drag on roughness obstacles, which does not apply to heat transfer. Thus z_T represents a parameterization of transport mechanism for heat in the immediate vicinity of the surface, where molecular viscosity and molecular thermal diffusivity of air may play a role[27]. The magnitude of the difference between the two roughness lengths is often described by a dimensionless number kB^{-1} defined as

$$kB^{-1} = \ln(z_o/z_T). \quad (20)$$

Thus kB^{-1} is the logarithm of the ratio between momentum and heat roughness length. Following Brutsaert[16], kB^{-1} is estimated from the relation

$$kB^{-1} = 2.46\,(\mathrm{Re}^*)^{0.25} - 2.0, \quad (21)$$

where Re* is the roughness Reynold's number given by

$$\mathrm{Re}^* = u^* z_o/\nu, \quad (22)$$

where ν is the kinematic molecular viscosity of air (1.461×10^{-5} m^{2}s^{-2}). To avoid anomalous outcome due to small values of u^*, we have set constraint to u^* as $u^* > 0.01$ ms^{-1} and considered unstable and neutral cases ($-0.5 < z/L < 0.02$). The mean value of kB^{-1} is about 18. In the literature, values of kB^{-1} ranging from 3 to 13 are reported (e.g. Braud *et al.*[21], Kohsiek *et al.*[28], Verhoef *et al.*[29]). The high value found over Anand leads to a low value of z_T calculated from eq. (20). Thus the value of z_T at Anand is 2.65×10^{-9} m.

Aerodynamic resistance (r_{aH}): The daytime course of wind speed ($u_{9.5}$) and aerodynamic resistance (r_{aH}) to heat transfer estimated from eq. (8) for 15 May 1997 is shown in Figure 6. It is seen from Figure 6 that r_{aH} decreases with increasing wind speed. It varies from 70 to 200 sm^{-1} when wind speed varies from 1 to 4 ms^{-1}. Stathers *et al.*[19] obtained r_{aH} = 100–125 sm^{-1} for homogeneous, dry, medium sandy bare soil at Delta, British Columbia where wind speed at 1 m varies between 1 and 3 ms^{-1}, and Holtslag and van Ulden[1] obtained 80 sm^{-1} for Prairie grass surface at Cabauw, the Netherlands for wind speed at 10 m between 2.5 and 6 ms^{-1}.

Figure 7 shows the scatter plot of observed values Q_{Hobs} (eddy correlation technique) against estimated Q_{Hcal} (bulk aerodynamic method) values of sensible heat flux. The scatter is very large, which can be attributed to various factors like the sensitivity of the instruments to the eddy correlation technique, computation of the value of kB^{-1} in eq. (21) and accuracy of the diabatic profile correction factors in eqs (9) and (10). The rmse is 25% of the observed mean value of Q_H. From the regression analysis it follows that $Q_{\mathrm{Hcal}} = 0.69\ Q_{\mathrm{Hobs}} + 29$, with correlation coefficient 0.75. Figure 8 shows the daytime course of Q_H for 15 May 1997. It is clear from Figure 8 that the sensible heat flux is in general underestimated.

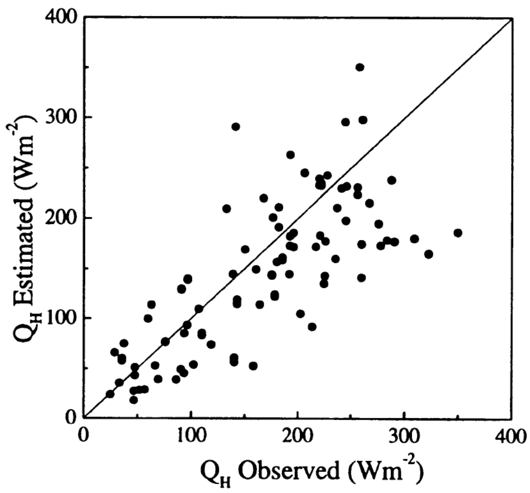

Figure 7. Comparison of observed values of sensible heat flux (Q_H) with estimated values from eq. (6) during 13–17 May 1997 at Anand.

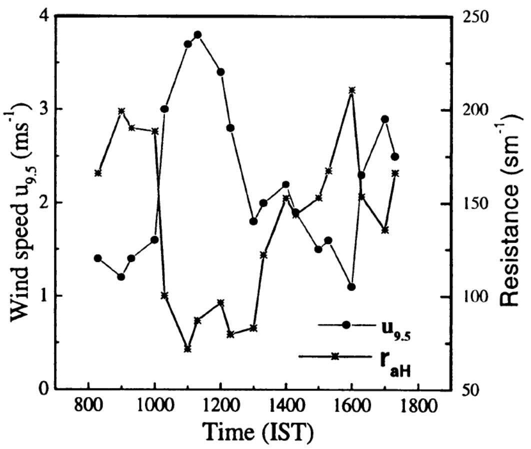

Figure 6. Daytime course of wind speed at 9.5 m height and aerodynamic resistance r_{aH} on 15 May 1997 at Anand.

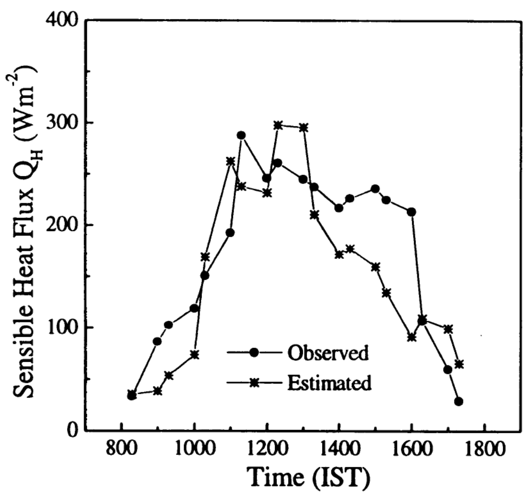

Figure 8. Daytime course of sensible heat flux (Q_H) on 15 May 1997 at Anand (observed and estimated).

Surface soil heat flux

Figure 9 shows the scatter plot of surface soil heat flux (Q_G) computed using eqs (17) and (18). It is seen that though the scatter is small, one-to-one correspondence between the values of Q_G estimated by two different methods is absent. The values of soil heat flux estimated by Fourier method are lower than those estimated by divergence method at the lower end. At the higher side, the estimated values by two different methods are more or less similar. From the least square analysis the regression line is fitted as Q_G (Fourier) = 0.62 Q_G (Divergence) + 81 with correlation coefficient 0.87. Figure 10 shows the daytime variation of Q_G. It is seen that the values of Q_G (Divergence) are always lower than Q_G (Fourier).

Surface temperature

Figure 11 shows the scatter plot of observed versus estimated (eq. (16)) values of surface temperature (T_s). The higher values of surface temperature are underestimated, whereas the lower values are overestimated. The rmse between the estimated and observed T_s is 5%, with the correlation coefficient of 0.99. Figure 12 shows the daytime course of T_s on 15 May 1997. It is clear from Figure 12 that T_s values are overestimated in the morning hours. They are quite close to each other during noon, whereas they are underestimated in the afternoon hours. This deviation is due to the assumption in eq. (16) that the surface temperature wave is sinusoidal. In practice, the diurnal forcing is not sinusoidal but a set of harmonics, so this equation is a crude assumption of the surface temperature[20]. A more appropriate solution is to represent the temperature forcing at the surface as a Fourier series. This part of the temperature will be considered in the forthcoming paper.

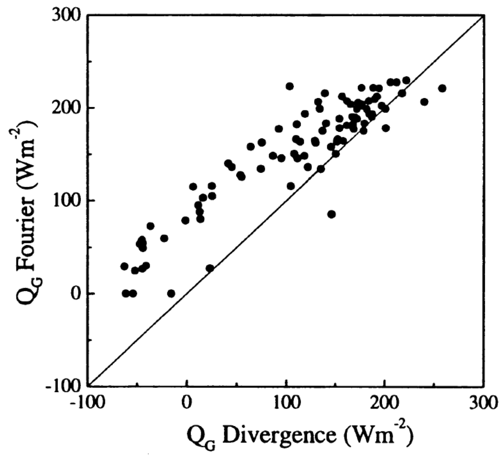

Figure 9. Comparison of surface soil heat flux (Q_G) estimated from eqs (17) and (18) during 13–17 May 1997 at Anand.

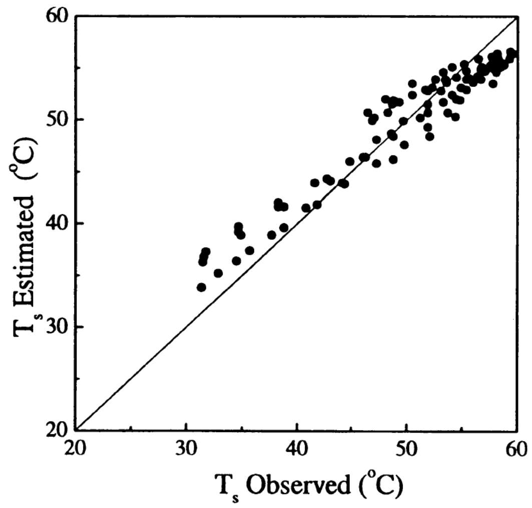

Figure 11. Comparison of observed surface temperature (T_s) with that estimated from eq. (16) during 13–17 May 1997 at Anand.

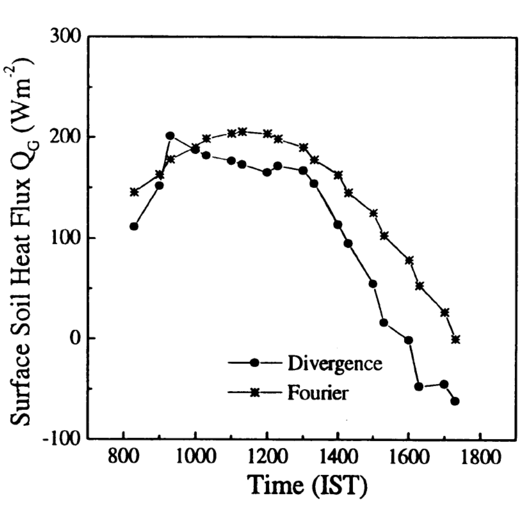

Figure 10. Daytime course of Q_G (Fourier) and Q_G (Divergence) on 15 May 1997 at Anand.

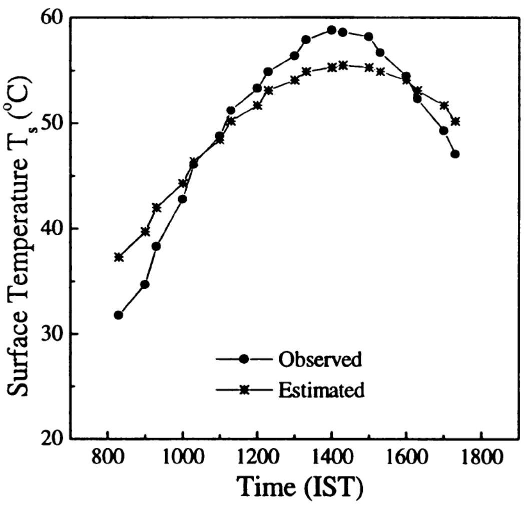

Figure 12. Daytime course of surface temperature (T_s) on 15 May 1997 at Anand (observed and estimated).

Summary and concluding remarks

The surface fluxes of radiation are estimated with standard as well as with some empirical formulae during daytime over a semi-arid station, Anand, Gujarat, in the western part of India. Empirical relationship between incoming short wave radiation and solar elevation angle is used to estimate the incoming short wave radiation. The attenuation coefficients (a_1 and a_2), the surface albedo (r) and the transmissivity (T_k) are computed using daytime observations over dry bare soil surface and clear sky conditions at Anand during the period 2–11 May 1997. The values of a_1 and a_2 are 1034 $\mathrm{Wm^{-2}}$ and 111 $\mathrm{Wm^{-2}}$ respectively. The surface albedo (r) is 0.21, whereas the transmissivity (T_k) is 0.659. The roughness lengths for momentum (z_o) and heat (z_T) are estimated with the observations from a sonic anemometer during 13–17 May 1997. The mean value of z_o is 0.2914 m. The parameter kB^{-1}, the logarithm of the ratio between z_o and z_T is observed to be 18 which leads to very low value of z_T (2.65×10^{-9} m). The estimated incoming short wave radiation with the empirical relationship shows rmse 3% only. The net radiation shows 8% rmse when the incoming short wave radiation values estimated with empirical relationship are used for computation, whereas rmse is 11% when the incoming short wave radiation estimated by standard formula is used to compute the net radiation. The sensible heat flux shows large scatter with rmse 25%. A linear relationship between observed (eddy correlation technique) and estimated (aerodynamic technique) values of sensible heat flux shows a correlation coefficient of 0.75. The surface soil heat flux is estimated by two different methods. The values estimated by divergence method are in general low throughout the day than those estimated by Fourier method. The estimated surface temperatures show small deviation from the observed values.

1. Holtslag, A. A. M. and van Ulden, A. P., *J. Climate Appl. Meteorol.*, 1983, **22**, 517–529.
2. Stull, R. B., *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht, 1988, p. 666.
3. Best, M. J., *Boundary-Layer Meteorol.*, 1998, **88**, 279–306.
4. Crawford, T. M. and Bluestein, H. B., *J. Appl. Meteorol.*, 2000, **39**, 1196–1217.
5. Sikka, D. R. and Narasimha, R., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1995, **104**, 157–187.
6. Rao, K. G., Narasimha, R. and Prabhu, A., in *The Monsoon Trough Boundary Layer* (eds Narasimha, R., Sikka, D. R. and Prabhu, A.), Indian Academy of Sciences, Bangalore, 1997, pp. 277–291.
7. Chattopadhyay, J. and De, U. K., *Indian J. Radio Space Phys.*, 2000, **29**, 81–87.
8. Padmanabhamurty, B., Rao, K. A. and Mukherjee, R., *ibid*, 1998, **27**, 199–206.
9. Satyanarayana, A. V., Lykossov, V. N. and Mohanty, U. C., *Boundary-Layer Meteorol.*, 2000, **96**, 393–419.
10. Nagar, S. G., Tyagi, A., Seetaramayya, P. and Singh, S. S., *Curr. Sci.*, 2000, **78**, 595–600.
11. Nagar, S. G., Tyagi, A., Seetaramayya, P. and Singh, S. S., *Boundary-Layer Meteorol.*, 2001, **98**, 297–314.
12. Shekh, A. M., Vernekar, K. G. and Keshavmurthy, R. N., *J. Agrometeorol.*, 2001, **3**, 31–37.
13. Nagar, S. G., Seetaramayya, P. and Singh, S. S., *ibid*, 1999, **1**, 125–136.
14. Srinivasan, *J. Boundary-Layer Meteorol.*, 1981, **21**, 173–181.
15. Smith, W. L., *J. Appl. Meteorol.*, 1966, **5**, 726–727.
16. Brutsaert, W. H., *Evaporation into the Atmosphere, Theory, History and Applications*, D. Reidel, Dordrecht, Holland, 1982, p. 219.
17. Garratt, J. R. and Hicks, B. B., *Q. J. R. Meteorol. Soc.*, 1973, **99**, 680–689.
18. Paulson, C. A., *J. Appl. Meteorol.*, 1970, **9**, 856–861.
19. Stathers, R. J., Black, T. A., Novak, M. D. and Bailey, W. G., *Atmosphere–Ocean*, 1988, **26**, 59–73.
20. Garratt, J. R., *The Atmospheric Boundary Layer*, Cambridge University Press, 1992, p. 316.
21. Braud, I., Noilhan, J., Bessmoulin, P., Mascart, P., Haverkamp, R. and Vauclin, M., *Boundary-Layer Meteorol.*, 1993, **66**, 173–200.
22. Mani, S. and Rangarajan, S., *Radiation Over India*, Allied Publishers, New Delhi, 1982, p. 646.
23. Idso, S. B., Baker, D. G. and Blad, B. L., *Q. J. R. Meterol. Soc.*, 1969, **95**, 244–257.
24. Polavarapu, R. J., *J. Appl. Meteorol.*, 1970, **9**, 809–814.
25. Rao Kusuma, G., Sethu Raman, Prabhu, A. and Narasimha, R., *Atmos. Environ.*, 1995, **29**, 2113–2129.
26. Gupta, R. K., Prasad, T. S. and Vijayan, D. J., *J. Agrometeorol.*, 2001, **3**, 189–215.
27. Sugita, M. and Brutsaert, W. H., *Water Resour. Res.*, 1990, **26**, 2937–2944.
28. Kohsiek, W., De Bruin H. A. R., The, H. and van Den Hurk B., *Boundary-Layer Meteorol.*, 1993, **63**, 231–230.
29. Verhoef, A., De Bruin, H. A. A. R. and van Den Hurk, B. J. J. M., *J. Appl. Meteorol.*, 1997, **36**, 560–572.
30. Haurwitz, B., *J. Meteorol.*, 1945, **2**, 154–166.
31. Lumb, F. E., *Q. J. R. Meterol. Soc.*, 1964, **90**, 43–56.
32. Collier, L. R. and Lockwood, J. G., *ibid*, 1974, **100**, 678–681.
33. Kasten, F. and Czeplak, G., *Sol. Energy*, 1980, **24**, 177–189.
34. Gul, M. S., Munner, T. and Kambezidis, H. D., *ibid*, 1998, **64**, 99–108.

ACKNOWLEDGEMENTS. We thank Dr G. B. Pant, Director, Indian Institute of Tropical Meteorology (IITM), Pune, for his keen interest in the present study. A.T. is thankful to the Indian Air Force, Pune for granting him study leave to carry out the research at IITM. The LASPEX-97 data are provided by the Boundary Layer and Land Surface Processes Studies group at IITM. S.G.N. thanks Dr T. Venugopal for fruitful discussions.

Received 18 December 2001; revised accepted 23 April 2002